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Laser applications have proliferated in recent years and, as to be expected, their presence is no longer confined to the laboratory or places where access to their radiation can be easily controlled. One obvious application where this is so is in military operations where various devices such as laser range finders, target designators, and secure communications equipment elevate the risk of exposure, specifically eye exposure, to unacceptable levels. Although the need for eye protection in the laboratory and other controlled areas has been appreciated since the invention of the laser, the use of lasers in circumstances where safety or the risk of temporary loss of vision, which can not always be ensured by administrative procedures, has made adequate eye protection essential. It is.

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the critical nature of many military operations that has driven the search for eye protection against both nuclear and laser radiation. At the same time, the requirement to maintain useful vision during irradiation as well as advances in laser technology have complicated the problem enormously. Pertinent aspects of the problem, such as laser characteristics--pulse width, repetition rate, laser wavelength tunability or agility, as well as effects on vision for various exposures have been estimated, as have the characteristics required of eye protective devices. Various classes of devices are discussed, and advantages and disadvantages noted.

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Laser eye protection

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ABSTRACT

Laser applications have proliferated in recent years and, as to be expected, their presence is no longer confined to the laboratory or places where access to their radiation can be easily controlled. One obvious application where this is so is in military operations where various devices such as laser range finders, target designators, and secure communications equipment elevate the risk of exposure, specifically eye exposure, to unacceptable levels. Although the need for eye protection in the laboratory and other controlled areas has been appreciated since the invention of the laser, the use of lasers in circumstances where safety or the risk of temporary loss of vision, which can not always be ensured by administrative procedures, has made adequate eye protection essential. It is the critical nature of many military operations that has driven the search for eye protection against both nuclear and laser radiation. At the same time, the requirement to maintain useful vision during irradiation as well as advances in laser technology have complicated the problem enormously. Pertinent aspects of the problem, such as laser characteristics--pulse width, repetition rate, laser wavelength tunability or agility, as well as laser power or energy, have been placed in perspective. In addition, possible effects on vision for various exposures have been estimated, as have the characteristics required of eye protective devices. Various classes of devices are discussed, and advantages and disadvantages noted.

1. INTRODUCTION

Laser applications have proliferated in recent years and, as to be expected, their presence is no longer confined to the laboratory or places where access to their radiation can be controlled. Military operations are obvious applications where various devices such as laser range finders, target designators, and secure communications equipment elevate the risk of exposure, specifically eye exposure, to unacceptable levels. Although the need for eye protection in the laboratory and other controlled areas has been appreciated since the invention of the laser, the use of lasers in circumstances where safety or the risk of temporary loss of vision, which can not always be ensured by administrative procedures, has made adequate eye protection essential. Adequate protection does not mean just protection against ocular injury, it means protection against ocular injury while at the same time maintaining sufficient vision to perform the tasks that may be required during laser exposure.

The major concern in the laboratory has been protection against eye injury and subsequent loss of vision. In a laboratory, where the characteristics of a laser are generally known, especially the wavelength, where administrative controls can be applied, and where there are no particular premiums placed on wide fields of view,

optical quality, light weight, etc, provisions for protective eyewear are relatively straight forward, uncomplicated, and inexpensive. However, the critical nature of many military operations, and the essential role vision plays in many of these operations, has led the military establishment into a search for adequate and usable eye protection; first against nuclear thermal radiations, and later, against laser radiation. It is this search for "adequate and acceptable" eye protection that is of interest because it has stimulated creativity and led to new ideas, approaches, materials, and problems. It is this aspect of laser eye protection that will be addressed, and in the military air operational environment in which it has been pursued. A brief review of the effects on eyes and vision that can result from excessive exposure to radiation will be presented to provide the background against which the development of specialized eye protection has been and is proceeding.

2. EFFECTS ON EYES AND VISION

Because the eye focuses incident light on the retina[1] (Fig. 1), thereby increasing the energy density of the incident light by a factor of almost 100,000, radiations from sources of intense light can produce undesirable effects on eyes at large distances[2] (Table 1). In the case of nuclear devices, the distance can be large due to the extremely large amount of energy that can be released in a detonation.[3] In the case of lasers, the distance at which ocular effects can be produced may also be very large, even for relatively small energies, because of the high directionality inherent in laser designs.

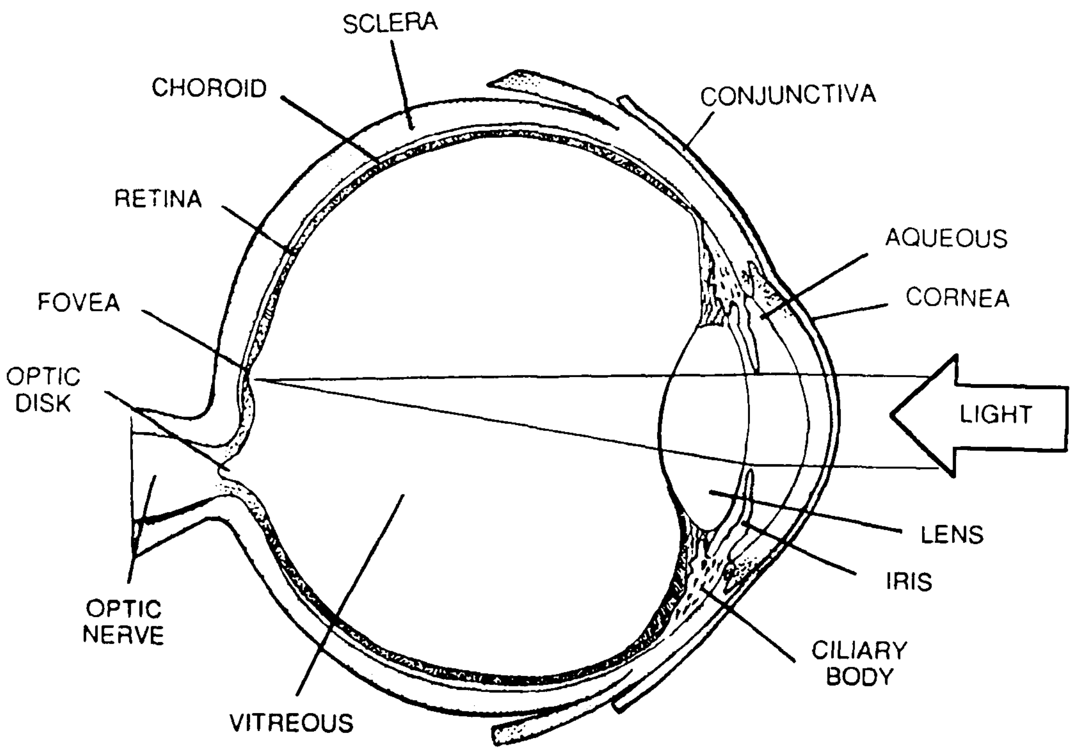

Fig. 1. Anatomy of the eye

TABLE 1. PREDICTED SEA LEVEL SEPARATION DISTANCES OF OCULAR EFFECTS FROM A 10 JOULE PER PULSE, 20-30 ns PULSEWIDTH LASER

	Laser Wavelength			
Ocular Effect	440 nm	532 nm	694 nm	1064 nm
MPE	56.8	64.9	78.1	57.9
1/2 x ED_{50} (MVL)	38.7	43.4	33.0	14.1
ED_{50} (MVL)	33.2	36.9	26.6	10.4
4 x ED_{50} (MVL)	23.3	25.4	16.5	5.5
1/2 x ED_{50} (VH)	12.9	13.6	12.6	4.8
ED_{50} (VH)	10.0	10.6	9.5	3.4
2 x ED_{50} (VH)	7.7	8.0	7.0	2.4

Note: Distances are in thousands of feet calculated using a mid-latitude, clear summer day atmosphere. MPE (Maximum Permissible Exposure), MVL (Minimum Visible Lesion), VH (Vitreal Hemorrhage), and ED_{50} (50% Probability of Occurance).

The ocular effects that can occur as a result of exposure to these sources depend upon several factors, particularly the characteristics of the radiating source, atmospheric conditions, and intervening media. For a source that emits visible radiation and near infrared radiation, effects encompass chorioretinal lesions up to and including hemorrhages, which can vary in size from sub-visible to optical disc size[4] (Fig. 2); flashblindness, a temporary effect which can last from a fraction of a second to several minutes[4] (Fig. 3); and veiling glare caused by light scattered intraocularly, by the atmosphere, and from transparent materials such as windscreens and goggles which may be positioned between the source of light and the eyes. Figure 4 shows profiles of forward scattered light from a helicopter windscreen material with various amounts of haze.[5] Since the atmosphere is not stable, in addition to attenuating the light, turbulance changes the spatial and temporal qualities of the transmitted light. Some typical effects of turbulance on the temporal transmission of light from a continuous wave low power visible laser are shown in Fig. 5.[6]

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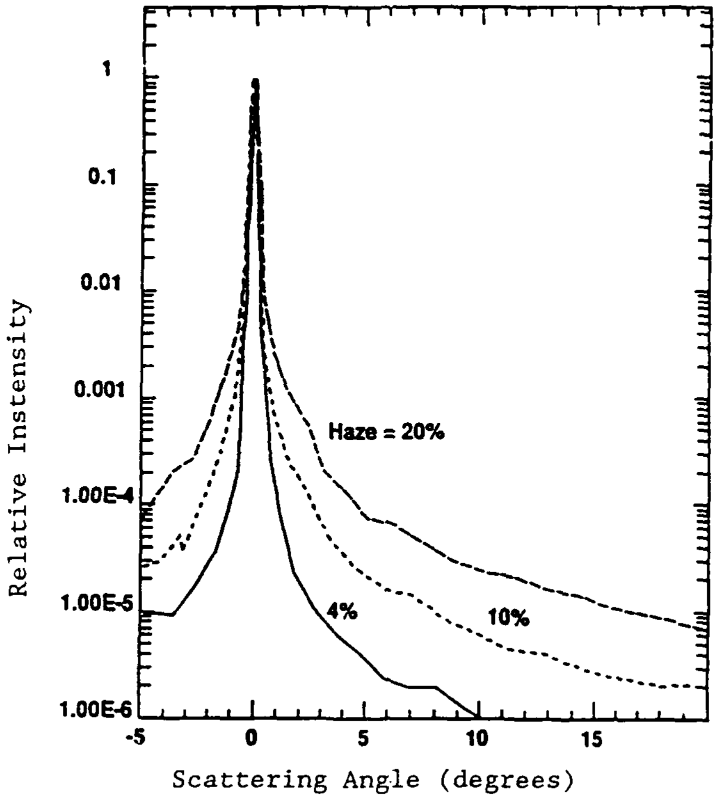

Fig. 4. Typical 632.8 nm scattering data from helicopter windshield material.

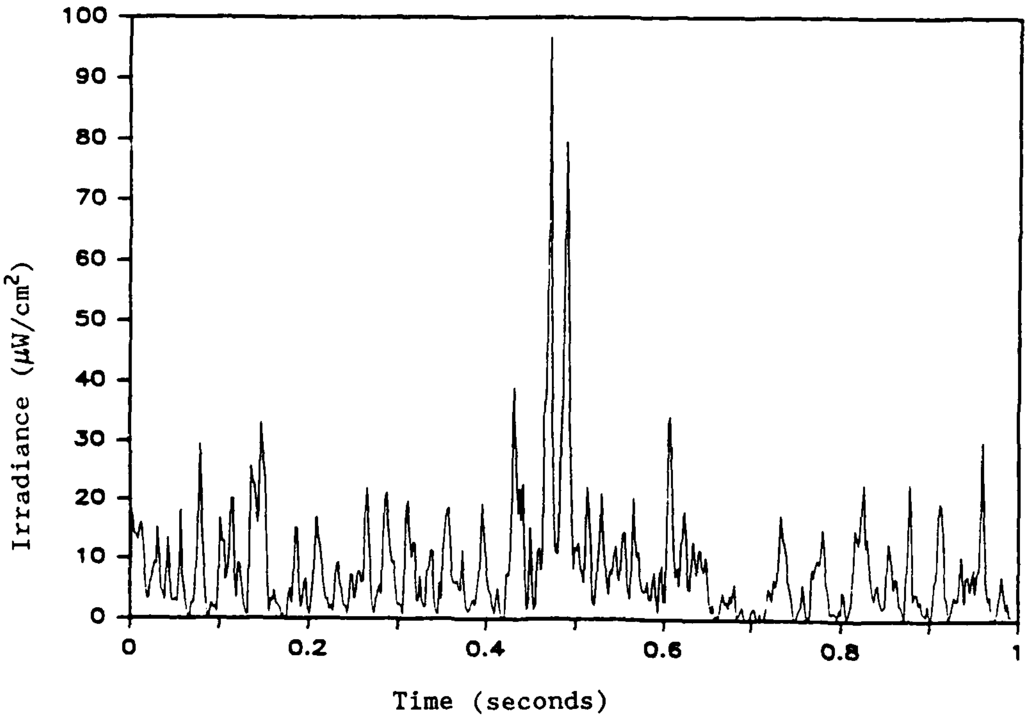

Fig. 5. Typical temporal fluctuations in CW 514.5 nm radiation over 1.5 km path.

The field of view obscured by laser glare produced by scattering from an aircraft canopy in a test at the Brooks AFB Laser Range is shown in Figure 6.[6]

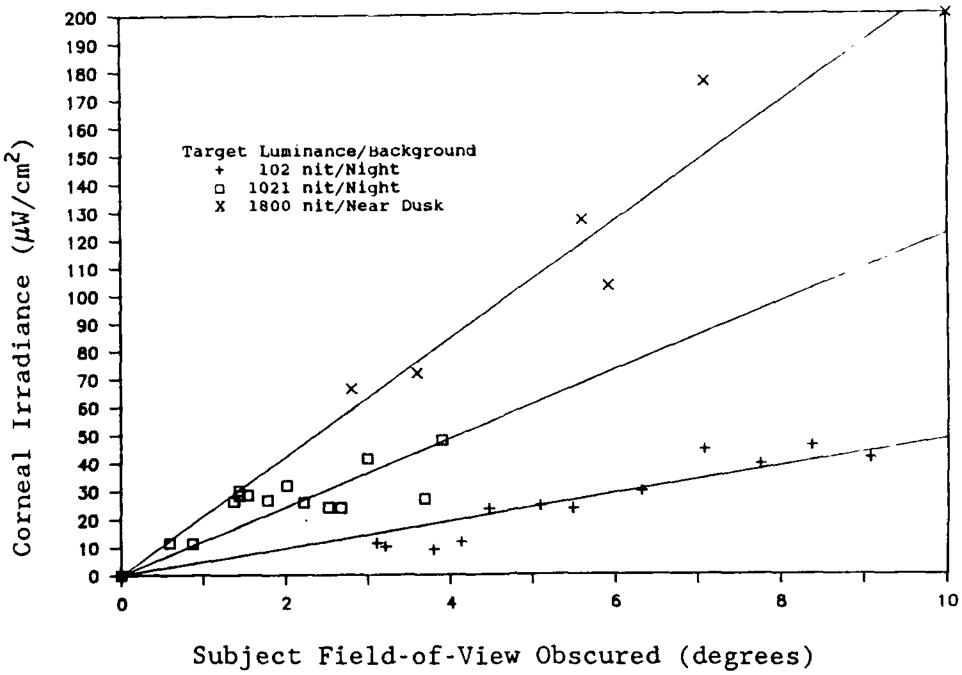

Fig. 6. Veiling glare produced by 514.5 nm CW laser on observers viewing a 10 minute visual field target through an aircraft canopy with three different target luminances.

Glare produces no afterimage and is not apparent when the light is extinguished or the visual target is relatively bright. Glare requires the least light energy to be bothersome, and is generally a problem only at night. Flashblindness requires a somewhat larger exposure than glare and the afterimage can be a problem following termination of the exposure. Flashblindness like glare, tends to be more troublesome at night when it is desired to see low luminance objects. Due to the relatively low light levels at which these effects occur, atmospheric effects can be a larger contributor to flashblindness and veiling glare than to the production of retinal lesions.

The production of permanent chorioretinal injury, with the potential loss of visual acuity, lies at the upper end of the eye effects exposure scale. Accompanying a retinal burn, no matter how small, there will generally be a surrounding area in which the light intensity may be sufficiently high to produce the bright afterimage of flashblindness. Vision will be recovered in this region in due course, but there will be some permanent loss of vision in the burned area and in the area immediately surrounding it where structural damage may have occurred. In any event, unless a retinal exposure is centrally located, and the affected area is large enough to include the entire fovea, it is unlikely that without complications, a "significant" permanent loss of vision will result, even if a permanent scotoma is present. Exposure levels for Q-switched lasers, at several wavelengths that will produce some of these effects, are shown in Tables 2 and 3.[2]

TABLE 2. SINGLE EXPOSURE EFFECTS (532 nm, 20-30 ns LASER PULSE)

Exposure Level	TIE(μJ)	Fovea	Extra Macular
MPE	0.2	Bright Flash	Flash
1/2 x ED_{50} (MVL)	1.5	Startle - Central Flashblindness Possible at Night	Flash
ED_{50} (MVL)	3	Startle - Central Flashblindness Probable at Night	Bright Flash - Startle
4 x ED_{50} (MVL)	12	Startle - 1/2° to 1° Lesion - Immediate Loss of Central Vision	Startle - 1/2° to 1° Lesion Brief Flashblindness Possible at Night
1/2 x ED_{50} (VH)	78	Startle - 2° to 3° Lesion Vitreal Hemorrhage Immediate Loss of Central Vision	Startle - 2° to 3° Lesion Contained Hemorrhage Possible Flashblindness Possible
ED_{50} (VH)	155	Startle - 2° to 4° Lesion Vitreal Hemorrhage Probable Immediate Loss of Central Vision	Startle - 2° to 3° Lesion Hemorrhage Probable Immediate Obscuration of Central Vision Possible
2 x ED_{50} (VH)	310	Startle - 3° to 5° Lesion 90% Probable Vitreal Hemorrhage - Immediate Loss of Central Vision	Startle - 3° to 5° Lesion 90% Probable Hemorrhage Immediate Obscuration of Central Vision Possible

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Note: TIE (Total Inter-ocular Exposure), MPE (Maximum Permissible Exposure), MVL (Minimum Visible Lesion), VH (Vitreal Hemorrhage), and ED_{50} (50% Probability of Occurance).

TABLE 3. EXPOSURE LEVELS FOR SINGLE 20-30 ns LASER PULSES

	Laser Wavelength			
Exposure Levels	440 nm	532 nm	694 nm	1064 nm
MPE	0.2	0.2	0.2	2.0
ED_{50} (MVL)	3	3	15	220
4 x ED_{50} (MVL)	12	12	60	880
1/2 x ED_{50} (VH)	80	78	120	1150
ED_{50} (VH)	160	155	240	2300
2 x ED_{50} (VH)	320	310	480	4600

Note: Values represent TIE in μjoules.

These ocular effects are not new. They have been known for decades, but extensive and systematic studies were not started until the early fifties--in connection with the problems presented by the thermal radiation emitted by nuclear detonations.[3]

The discussion above applies to nuclear thermal radiation as well as to laser radiation, with the major differences being: (1) nuclear thermal radiation occurs across a very broad band, but insofar as retinal effects are concerned covers only a wavelength band extending from about 400 to 1400 nm, and (2) since a nuclear fireball is an extended source, it will be imaged on the retina as a finite source which can range from minimal visable image size to a millimeter or more in diameter. In contrast, direct laser radiation will be imaged with a "point source" distribution. The wavelength band extending from 400 to 1400 nm is frequently referred to as "in-band", and identifies that portion of the spectrum that will reach the retina. Laser radiation can be in-band or out-of-band, depending on the designed laser wavelength. Part of the nuclear thermal radiation lies out-of-band, but since very little out-of-band radiation reaches the retina, it is ineffective in producing retinal effects.[3] This does not mean that out-of-band radiation can not cause ocular injury, it can! However, out-of band radiation, which consists of the ultraviolet and far infrared portions of the spectrum, is absorbed primarily in the cornea and lens, whereas in-band radiation is transmitted through the clear media of the eye with relatively little loss. It is interesting to note that significant corneal injury would result in immediate and extended loss of useful vision through pain, tearing, and corneal deformation. Fortunately, a number of transparent plastics and glasses, frequently present in aircraft canopies and windscreens, are very efficient absorbers of out-of-band radiation, therefore these radiations do not generally pose a problem inside aircraft.[7] Also, some plastics and special glasses are efficient absorbers of near ultraviolet and near infrared radiation and can be used effectively in eye protection against these radiations.

3. EXPOSURE CHARACTERISTICS THAT DRIVE EYE PROTECTION DESIGN

The characteristics of a light source govern, in large part, the kind of eye protection that is needed. The visible thermal emission from a nuclear detonation, sometimes called the "nuclear flash" comes in two major pulses; one very soon after detonation initiation and the second somewhat shortly after the first--but lasting much longer. The thermal emmission spectrum resembles that of a black body radiator at temperatures ranging from below 5000 degrees K to perhaps 30,000 degrees K, depending upon various factors. In general, both pulses are capable of producing injury. As a result, either a passive neutral density filter is needed, one that provides sufficient optical density across the emission spectrum to reduce the exposure to an acceptable level; or a dynamic neutral density filter that switches "on" in a time sufficiently short to prevent a retinal burn or significant flashblindness. Since a passive neutral density filter of sufficient optical density to protect the retina from injury would also severely restrict normal vision, a dynamic device is more desirable for aircrew protection, provided the open state optical density permits adequate vision to perform the tasks that are necessary, and provided it does not increase the risk inherent in the mission.

In an attempt to solve the nuclear problem, a number of concepts and devices were considered, among them photochromic materials, UV-pumped photochromics, various mechanical devices, polarization schemes, thermal curtains, eye patches, and one notable device in which carbon particles were driven between two pieces of clear plastic, forming the lens of a goggle, by an explosive squib that was triggered by the early UV emittance of a detonation. It was only after years of searching that a reasonable solution to this problem was found when PLZT (lanthanum-modified lead zirconate titanate) was invented at the Sandia Laboratory--and then, PLZT could not meet the design specifications until the open-state transmittance specification was lowered from 70% to 20%. The PLZT goggle still has several undesirable features, among which is a significant angle of incidence effect (as have all polarization-based devices) and a temperature effect, and has not found acceptance by all potential Air Force users.[8]

How does the laser eye protection problem differ from the nuclear problem? At first, they appeared to be radically different, with the laser problem solvable by passive "notch" filters, so called because unwanted bands in the visible spectrum could be removed by narrow band absorption, or by reflection filters leaving sufficient transmitted light for visual task performance - Fig. 7. Such filters have been available for laboratory use for many years. This technique has been refined, special dyes developed, and processes for tailoring reflection filters devised that have produced some usable eyewear for field as well as aircrew use. When developed for field use, eyewear must be capable of withstanding prolonged exposure to sunlight, stable in extreme environments, compatible with existing life support ensembles, and impact resistant. If the eyewear is to be used in an aircraft, it must also be compatible with cockpit lighting, tolerant of G-forces, and ejection seat compatible. In addition, acceptable eye protection must also provide optical densities capable of providing the desired wavelength protection, usable photopic and scotopic luminous transmittances, excellent optical quality, and configurations and weights suitable for use by aircrews during day as well as night conditions. A device meeting all of these requirements has not yet been demonstrated.[9,10]

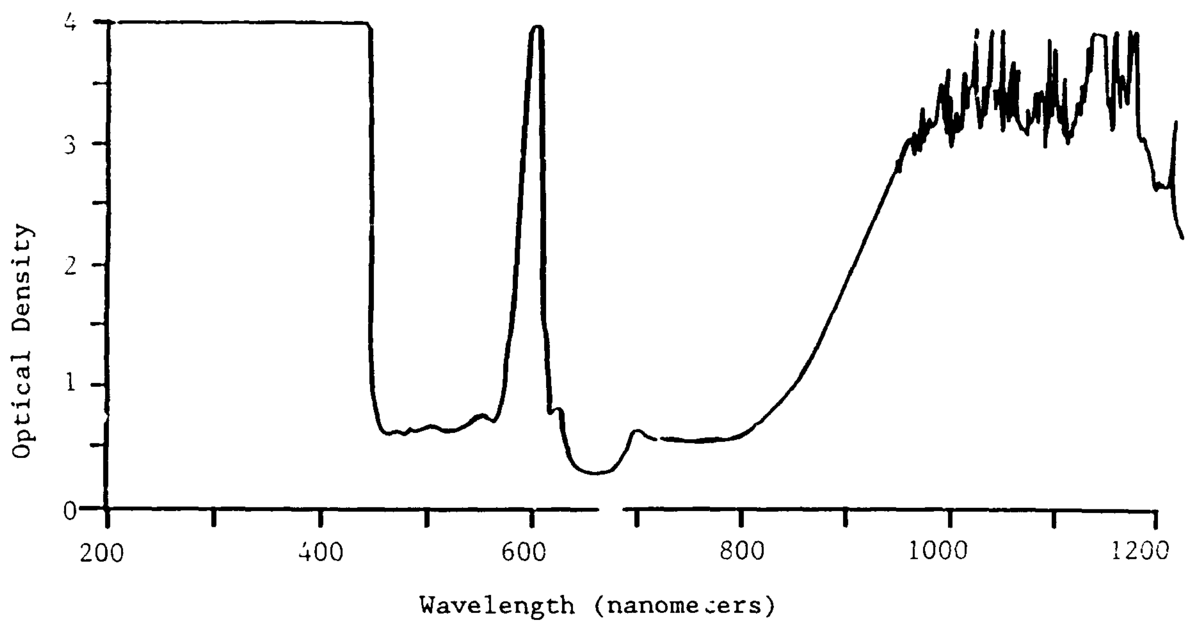

Fig. 7. Optical density curve of a generic notch filter laser eve protection.

In the mean time, technology has over-taken the "notch" filter approach. Tunable lasers that can be configured to produce several wavelengths, usually one at a time, have been available in the laboratory for a number of years. Further, lasers in which tunability can be accomplished rather quickly (agile lasers), or which produce multiple wavelengths simultaneously, are feasible. Thus, the concept of passive notch filter eye protection, such as described previously, is not adequate for the future since it can be defeated by existing laser technology. All that is required to stimulate agile laser production for use by the military is an advocate. An alternative approach to laser eye protection appears to be a broad band dynamic device (fast switch) that will provide sufficient optical density in a sufficiently short time to limit anticipated exposures to acceptable levels. In this context, short means a few nanoseconds or less, in contrast with 10's of microseconds in the case of nuclear detonations, and broad band means covering the entire visible spectrum (400 to 750 nm). Such a device might resemble the nuclear flash "solution" rather closely, except for the speed of closure. It is noted that such a device should remain "closed" until the incident light is reduced to some unobjectionable level. If such a protective device were to be mounted on the head (visor or goggle), a difficulty in seeing dimly lit objects would exist while the device was in the "closed" state. This may not be a serious problem for a nuclear flash since, by virtue of its four-pi emittance, the entire vicinity surrounding a detonation, and probably the aircraft, may be brightly illuminated. Because of beam directionality, this will not be the case for a laser source. In this case, a dynamic device, when "closed," would prevent useful vision both inside and outside a cockpit, except perhaps to locate the position of the laser. If a wide field of view device could be mounted at the windscreen in an acceptable configuration, or if a device were mounted on the head and, a path provided for vision inside the cockpit that was not available to the incident laser light, vision inside the cockpit could then be preserved--although vision outside the cockpit would be interrupted. These kinds of arrangements have been considered, but have not yet been developed in configurations that are attractive to potential users.

Exposure to a nuclear detonation is traditionally treated as a continuous exposure, as is exposure to a continuous wave laser. In each case, nuclear or laser, protection must be provided until the illumination is terminated or is reduced to an unobjectionable level. In the case of multiple pulse lasers, a laser that is repetitively pulsed at a rate greater than about 20 hertz is effectively a continuous source in terms of its effect on vision. When looked at in terms of the time between relatively short pulses, blocking each of the individual pulses in a train of pulses, while leaving a period for clear vision between each pulse could provide essentially uninterrupted visi . As a consequence, consideration has been given to synchronizing a shutter of some kind with incoming laser pulses to provide protection while preserving vision. Unfortunately, to date no method has been developed that will protect against the first pulse. Methods have been conceived that will provide a "statistical" protection from the first pulse, i.e., a finite probability exists that exposure to the first pulse will occur. However, these devices have not been reduced to working prototypes, much less incorporated into configurations that could be proposed for testing and user evaluation.

A great deal of effort has gone, and is going, into the search for and development of broad band "fast switch" materials having the potential of "closing" very rapidly--some in less than a nanosecond. This effort has many of the characteristics of basic research, and in general, it is too early to predict the outcome in terms of eye protection devices that will be acceptable in a combat environment. However, some features are apparent. All these nonlinear materials have one thing in common; they must be located in a focal plane of an optical system in order to provide flux densities sufficiently high to transition their response into the nonlinear region where they act as optical limiters. Also, some of the materials respond essentially as absorbers, some as diffusers, and some as a combination of the two. Device design must not only provide protection against injury, but assure that any light that reaches the eye does not produce an objectionable glare or flashblindness. Accommodating these features will probably move a device further from the goal of a simple lightweight, wide field of view visor or goggle with excellent optical quality. It may develop that fast switch materials find their most useful place in the protection of sensors other than eyes.

Another concept that has received attention is the tri-stimulus visor. This is an old concept that has been recently revived. This scheme is the reverse of the notch filter in that it blocks all wavelengths except those which lie in 3 fairly narrow bands, one positioned in each of the 3 primary color regions of the visible spectrum. The problem with this concept is that the luminous transmittance will be quite low. This may be acceptable in bright daylight, but the utility of such a device will decrease as the ambient light level is reduced, and will become unsatisfactory for viewing low luminance objects at night. Also, this concept can be defeated by a "white light" laser or a "scanning" agile laser.

4. CONCLUSIONS

It is hard to ignore the similarities that exist between the search for nuclear flash eye protection and the search for laser eye protection. The basic problems are similar, but not the same. Agile laser technology has increased the similarity, but the laser still appears to present a more difficult problem due to the very short fast rise time pulses that can be produced, the very high intensities that can be achieved, and the very small beam divergences that are possible. Even though the nuclear flash

problem has not been satisfactorily resolved, there does not seem to be an active research and development program aimed at its resolution. Perhaps this is because it is felt that a resolution of the laser problem will also provide an acceptable resolution to the nuclear problem. This may or may not be the case, and even then, the laser solution may not be the best, optimum, or least expensive solution for the nuclear case. However, the recent development of a nematic liquid crystal materal may provide a similar, but less expensive, substitute for PLZT.

Cost, utility, and user acceptance will all play a part in finding a solution to the laser eye protection problem, or perhaps several solutions each tailored for a particular scenario. Aircrews will judge the acceptability of potential solutions on the basis of their perception of the laser threat (soft kill) versus other threats (hard kills) with which they are familiar. If, in their view, laser eye protection increases vulnerability to hard kills, they are likely to reject it in favor of tactics, or some other means, to reduce the effect of lasers on the achievement of their objectives. It may be that the problem of providing adequate direct laser eye protection is so intractable that resorting to indirect viewing of the "outside" world at critical times will be necessary in some scenarios. At this time, the problems of providing protection for the sensors that supply information for visual displays inside aircraft appear more amenable to solution than do the problems of providing acceptable laser eye protection. In any event, it is quite likely that acceptable solutions to laser eye protection for aircrews will be arrived at in a manner similar to that which led to "acceptance" of PLZT for nuclear flash protection, i.e., relaxation of specifications and compromises on user acceptance requirements, thereby bringing together what can be done at the time with what will be accepted by the users.

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